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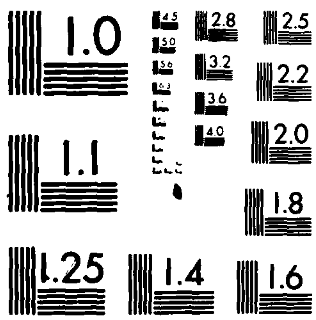

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RADIATION/CATALYTIC AUGMENTED COMBUSTION

MOSHE LAVID
CORPORATE RESEARCH-TECHNOLOGY FEASIBILITY CENTER
EXXON RESEARCH AND ENGINEERING COMPANY
LINDEN, NEW JERSEY 07036

JULY 1981

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FINAL TECHNICAL REPORT AFOSR-TR-81-
CONTRACT NUMBER F49620-77-C-0085

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THIS REPORT HAS BEEN RELEASED BY H. C. Hayworth
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MANAGER
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FOREWORD

This is a final report on research in Radiation/Catalytic Augmented Combustion conducted with partial support of the Air Force Office of Scientific Research under Contract F49620-77-C-0085, with Dr. B. T. Wolfson as the AFOSR project monitor. This report covers the progress of research during the entire contract period; from the date of inception June 1, 1977 to the date of completion February 28, 1981. The work was performed at Exxon Research and Engineering (ERE) Company, Linden, New Jersey with Drs. A. E. Cerkanowicz and M. Lavid as Principal Investigators. Dr. Cerkanowicz was the principal investigator from the date of inception thru August 1980, when Dr. Lavid assumed responsibilities until completion date. Within Exxon, the work was carried out in the Corporate Research-Technology Feasibility Center, Contract Research Division.

A new contract F49620-81-C-0028 has just begun at ERE to further study Radiation/Catalytic Augmented Combustion under flow conditions.

ABSTRACT

This is a final report on the progress of research in Radiation/Catalytic Augmented Combustion. This research encompasses two promising techniques for extending aircraft operational range. They are radiative and catalytic augmentation techniques to enhance combustion initiation and reaction kinetics which restrict combustor operation via limits on flammability, flame propagation, ignition and stability. Both techniques have demonstrated the capability to enhance combustion processes and to broaden normally encountered stability limits. The radiative technique under laboratory static conditions has successfully ignited fuel-air mixtures, and has enhanced combustion processes, utilizing pulsed and continuous VUV light sources. Similarly, the catalytic technique has provided efficient combustion under normally difficult fuel lean, low temperature, conditions. A complementary effort involves the development of analytical capability required for modeling the radiative and catalytic techniques.

Radiative ignition and combustion enhancement tests have been performed on gaseous mixtures under various static conditions. Successful radiative ignitions were obtained with pulsed and continuous VUV/UV light sources. The ignition with the continuous light source was reported for the first time. Combustion enhancement experiments were conducted with continuous irradiation. Encouraging enhancement results of higher flame propagation velocities and larger extinction times and extinction distances were also reported for the first time.

Catalytic combustion, in this program, was primarily aimed at improving flame stabilization and reducing pressure loss in aircraft afterburner systems. To this end, a conceptual design of a catalytic flameholder was evolved from an initial configuration of straight uniform cells to graded cells and finally to converging cells. The converging cells, in addition to offering an increase in resistance to blow-out and an increase in throughput, as the graded cells, offer also smooth convergence and upstream (where combustion is most unstable) heat radiation.

A new contract (F49620-81-C-0028) has begun to further research, the radiative and catalytic techniques. Its main objective is to investigate these promising techniques under more realistic conditions of sustained combustion in flowing systems.

TECHNICAL OBJECTIVE AND APPROACH

AF FUNCTION - Advanced air-breathing engines, airborne reconnaissance and transport, weapon delivery and defense.

DEFICIENCY - Present aircraft operation is limited by combustion associated phenomena such as flammability, flame propagation, ignition and stable combustion. Moreover, current understanding of basic mechanisms and processes associated with new techniques for initiation and enhancement of combustion is limited and insufficient.

OBJECTIVE - To investigate and evaluate the feasibility of two promising techniques: radiative and catalytic, for extending current aircraft operational limitations which are encountered due to combustion associated phenomena. To develop analytical capabilities required to model the above outlined combustion phenomena utilizing these augmentation techniques.

APPROACH - This program has encompassed investigation and feasibility assessment of these two promising techniques to enhance combustion initiation, and reaction kinetics which restrict combustor operation via limits on flammability, flame propagation, ignition and stability. Both techniques have demonstrated the capability to enhance combustion processes, and to broaden normally encountered stability limits. The radiative technique under laboratory static conditions has successfully ignited fuel-air mixtures, and has enhanced combustion processes, utilizing pulsed and continuous vacuum ultraviolet (VUV) light sources. These encouraging laboratory experiments have supported the theory which postulates that selected wavelengths of vacuum ultraviolet radiation effectively split oxygen molecules into highly reactive oxygen atoms. These oxygen atoms quickly build up to a critical concentration in a fuel-air mixture, resulting in the initiation of chain reactions which, in turn, rapidly initiate and enhance combustion. Similarly, the catalytic technique has provided efficient combustion under normally difficult conditions of low temperatures and fuel-lean mixtures. In this technique combustion is promoted by the use of a solid surface coated with an appropriate catalyst which accelerates chemical reactions. In most applications, the promotional catalytic effects are only needed to stimulate the combustion system to the point where normal gas phase reactors become dominant. As part of the new contract, further characterization of enhanced ignition and combustion by radiative and catalytic techniques at aircraft combustor and afterburner conditions will be explored in a plug flow combustor, simulating realistic flow conditions. Various catalytic flameholder configurations, designed to improve flame stabilization and to reduce pressure loss, will also be tested under afterburner conditions. Finally, a complementary effort has been undertaken to develop mathematical models describing radiative and catalytic ignition and combustion enhancement phenomena. The resulting model predictions have been used as adjunct to the experimental effort to broaden our understanding of the underlying physical and chemical interactions. Furthermore, they have provided constructive inputs and guidelines for best test conditions yielding performance optimizations. In term, experimental data have been compared to analytical predictions and when diagreement was noted the model was revised until good agreement was obtained.

STATEMENT OF WORK

The final work statement covering the entire contract period June 1977 thru February 1981 is presented below. This work statement was expanded in April 1979 to include the study of combustion augmentation by both, photochemical and catalytic techniques.

The contractor shall furnish scientific effort during the funding period, together with all related services, facilities, supplies and materials, needed to conduct the following research.

a. Identify, acquire and evaluate appropriate vacuum ultraviolet and ultraviolet light sources. Purchase of available and specially modified sources will be pursued under subcontract. Source requirements will be specified based on photochemical combustion requirements previously determined under AFOSR contract F44620-70-C-0051 and AFAPL contract F33615-73-C-2063.

b. Select and characterize radiant sources for program use. Spectrographic measurements will be employed to determine wavelength dependence of source energy output as a function of energy input and pulse duration. Pulsed sources will be evaluated in the 145-245 nm range and continuous sources will be evaluated in the 200-360 nm range. Combustion initiation tests using static mixtures will also be performed to further characterize the source radiant beam.

c. Initiate experimental tests to identify and investigate the details of radiant beam-reactant mixture interaction. Explore the effects of inerts, fuel-free air zones, and depth of radiation penetration on the photo-combustion processes using gaseous, stationary reactant mixtures. Also design and initiate plug flow combustor experiments to provide for characterization of radiative effects in flowing reactive mixtures.

d. Carry out a comprehensive technical analysis to complement the experimental program. The detailed aspects of radiation-combustion interaction which lead to ignition and combustion enhancement will be considered. A consistent experimental and theoretical description of combustion augmentation will be developed.

e. Extend experimental tests on gaseous, stationary reactant mixtures to include investigation of the effect of radiant energy on the ignition and flame propagation of spark ignited mixtures. Attempt to obtain ignition using a focused, continuous light source.

f. Employ plug flow combustor experiments to investigate ignition and flame attachment in flowing reactive mixtures subjected to pulsed vacuum ultraviolet sources. Also study flame stabilization by continuous ultraviolet irradiation.

g. Design and initiate cannular combustion experiments to provide for characterization of radiative effects in non-premixed flowing reactive mixtures.

h. Utilize the experimental data and computer model to develop a consistent description of radiative augmentation processes. Undertake model revisions and refinements as necessary.

i. Perform cannular combustor experiments to investigate ignition and flame attachment in flowing, liquid-fuel, unpremixed, reactant systems subjected to pulsed vacuum ultraviolet and continuous ultraviolet irradiation.

j. Identify and evaluate alternate combustion augmentation techniques for application in practical combustion hardware. Carry out simple, preliminary experimental tests of the most promising techniques as appropriate.

k. Expand the radiative enhancement model to include methane-fueled system kinetics. Perform additional analysis to parametrically characterize radiative enhancement and to assess application feasibility.

l. Develop a comprehensive test plan for larger scale engine tests of the radiative augmentation techniques, including a parametric test matrix.

m. Develop a simple model of the catalytic flame stabilization process including salient features of the aerothermochemistry of the catalytic combustion mechanism and conventional flame-holding mechanism. Utilize the model to perform parametric analyses to assist the experimental program and to initially analyze experimental data.

n. Design, fabricate and commission (shake down) an experimental flame-stabilization test facility which provides atmospheric reactant flow conditions at gas velocities up to 200 m/s and gas temperatures up to 1000 K.

o. Perform initial experimental flame-stabilization tests on a standard V-gutter, non-catalytic monoliths and catalytic monoliths under both non-reacting and reacting flow conditions. These tests will use one specific fuel and two commercially available catalyst types. Experimental variables will include inlet mixture ratio, temperature, and velocity.

p. Evaluate important combustion mechanisms using a specially fabricated stabilizer, with a sintered metal disk on the downstream side through which hot gases or products of partial fuel oxidation can be passed. Experimental variables will include fuel type, temperature and velocity.

STATUS OF RESEARCH EFFORT

This section summarizes the entire program research accomplishments which were partially reported in three annual reports [1,2,3]. It covers the work performed since the date of inception, June 1, 1977 to the date of completion February 28, 1981. Evaluation, selection, and acquisition of three suitable vacuum ultraviolet and ultraviolet lamps have been completed. Spectrographic diagnostic tests for two of the light sources have been performed and analyzed. The newly obtained spectral information has been incorporated into the analytical radiative model. This radiative initiation model has been revised to include the effects of light source characteristics, photodissociation, kinetics (including electronically excited state species), and adiabatic temperature rise. The model has shown good phenomenological agreement with experimental results. Extensive static experiments have been conducted to demonstrate radiative ignition and combustion enhancement. Minimum ignition energies have been measured for various gaseous fuels as a function of equivalence ratio using a pulsed light source (ILC). For the first time radiative ignition was demonstrated with a continuous light source (EIMAC). Using the same continuous light source very encouraging enhancement results have been observed and measured. In the catalytic program, a new model for catalytic flameholding devices has been developed. It still has to be reviewed and then revised. The conceptual design of the catalytic flameholder has evolved from the initial configuration of uniform cells to graded cells and finally to converging cells.

- Light Source Acquisition and Characterization

Fourteen light source manufacturing specialists were contracted and their capabilities evaluated with regard to the specified light source needs. As a result of this evaluation [1], three light source systems, outlined in Table I were selected and acquired for use in the program. The VUV source required some development effort and was based on improved versions of the previous designs utilized for photochemical ignition. The UV and combined VUV/UV sources were selected essentially from product lines after a thorough screening process.

The first system was received from ILC. It included ten pulsed VUV lamps with a power supply suitable for ignition experiments. The second system was shipped from Optical Radiation Corporation (ORC). It included a 1 kW continuous UV lamp suitable for combustion enhancement tests. The third system was bought from EIMAC (a Division of Varian). It consisted of a 0.5 kW continuous VUV/UV lamp with sapphire window and focusing reflector installed in a special housing. This lamp was found to be suitable for ignition as well as combustion enhancement tests. Two more lamps were ordered after the first one cracked during an ignition experiment. The first lamp has a regular sapphire window, and the second lamp has a UV grade polished sapphire window. The possibility of using a VUV laser as a fourth light source has also been explored. The Lumonics TE-861 and the Lambda Physik EMG-200 Excimer laser systems were identified as the most suitable for our experimental needs. The logistics and the conduction of the radiative experiments with these lasers are being pursued in the new Contract (F49620-81-C-0028).

TABLE I

RADIATIVE AUGMENTED COMBUSTION PROGRAM LIGHT SOURCE SYSTEMS

Source	1-VUV	2-UV	3-VUV/UV
Spectral Range	140-200 nm	200-400 nm	150-400 nm
Window	UV Grade Sapphire	High Grade Quartz	Normal and UV Grade Sapphire
Optics	Point Source with No Collecting Optics	Focused by Elliptical Reflector Lens Assembly for Parallel Beam	Focused - Elliptical Reflector Sealed in Arc Chamber
Optical Path	Zero, Evacuated	Air	Zero, Evacuated, Air
Mode	Pulsed, $\tau < 10^{-4}$ s	Continuous	Continuous
Energy/Power Input	0.5 to 50 J	0 to 1 kW	0 to 500 W
Plasma Source	Xenon Short Arc	Mercury-Xenon Short Arc	Xenon Short Arc
Approx. Pressure	300 kPa	300 kPa	300 kPa
Combustor Function	Ignition	Enhancement	Aspects of Ignition/Enhancement
Supplier	ILC	ORC	EIMAC

Spectrographic diagnostic tests have been performed to characterize the EIMAC and ILC sources which exhibited successful radiative results. Radiant output intensity and total energy measurements have been made as a function of spectral wavelength (140-380 nm), pulse time, and input energy or power. This data, which provides a comprehensive description of light source behavior has been analyzed and reported in the second contract report (AFOSR-TR-79-1096) [2]. Data on the continuous EIMAC source indicated that very little line radiation is present in the spectrum which shows a continuous drop in intensity with decreasing wavelength except for a small peak at about 165 nm. For power levels less than about 400 watts, radiant power output in the vacuum ultraviolet varies linearly with input power.

The spectral distribution of intensity for the pulsed vacuum ultraviolet light sources supplied by ILC has pronounced peaks in the 145 to 175 nm wavelength region. This is a region of photon energy which is extremely effective in initiating combustion reactions. Thus, the spectral data clearly support the unique ability of these light sources in radiative ignition applications. The experimentally measured pulsed VUV source intensity spectrum is shown in Figure 1. Such detailed spectral information is critical in correctly modeling the influence of VUV photons on the chemical kinetics of interest. Equally important is the pulse shape (intensity vs. time) behavior of the photon flux. Although the pulse shape was found to vary with wavelength, the time integrated value (energy deposition vs. time) could be correlated by assuming a pulse shape which corresponds to a classical critically damped discharge. Figure 2 shows a comparison between measured and analytically modeled pulse shapes for wavelength regions at 143.5, 146.5, 166.5 and 177.5 nm.

Above input energies of about 6J the pulse became undamped. As a result, the time required for total energy input increased considerably and the input energy conversion efficiency decreased. Consequently, data interpretation and comparison with single pulse inputs become difficult. Continued need of energy levels that result in undamped discharge will necessitate redesign of the discharge circuitry.

- Static Experiments

The experimental combustion work has been conducted under static conditions at the Combustion Enhancement Laboratory. The experimental apparatus, depicted schematically in Fig. 3, provides the capability of studying the interaction of vacuum ultraviolet and ultraviolet radiation with gaseous fuel-air and fuel-oxygen mixtures, at subatmospheric and atmospheric pressures and at room temperature. A quartz cylindrical combustion chamber 2.5 cm diameter and 30 cm long can be irradiated end-on by light sources of various types. An adjustable length cell is used between the combustion chamber and the light source in order to provide a diagnostic procedure to evaluate radiation optics and absorption effects. The cell is evacuated or filled to various pressures with air, oxygen, or nitrogen. Current light sources capability includes three high pressure xenon or mercury-xenon plasma arcs optimized for different wavelength regions as follows:

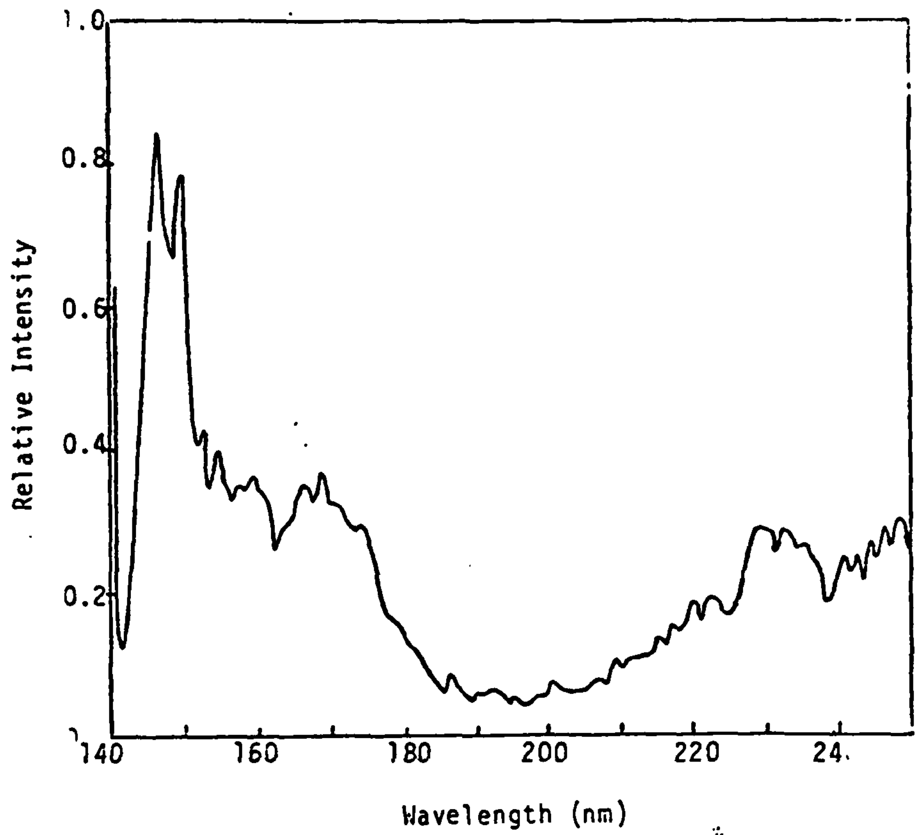


Figure 1 - Spectral Distribution of Intensity for Pulsed VUV Light Source

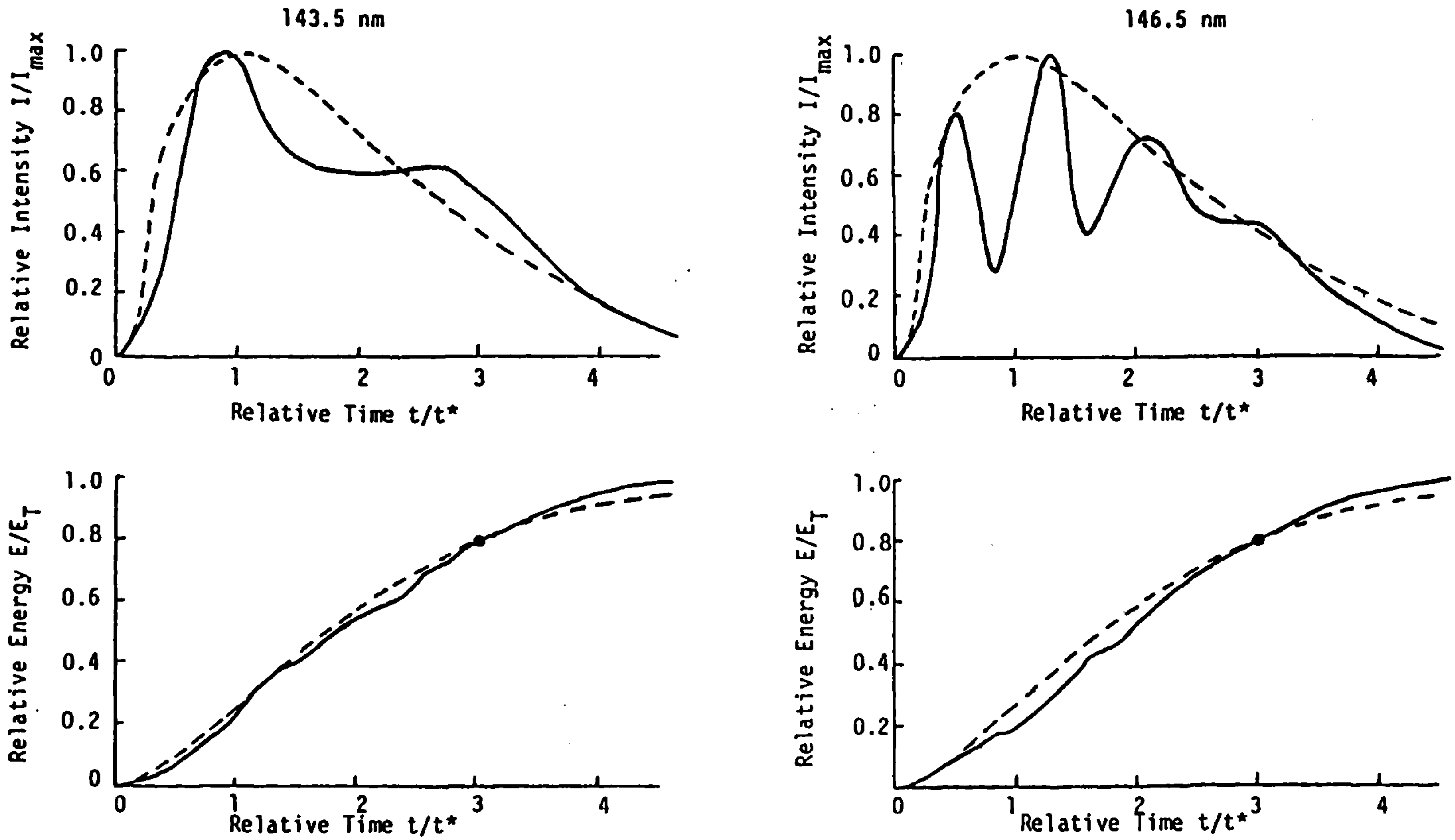


Figure 2 - Relative Values of Intensity and Energy vs Time for Pulsed VUV Light Source: Experimental (Solid Curve), Critically Damped Representation (Dashed Curve)

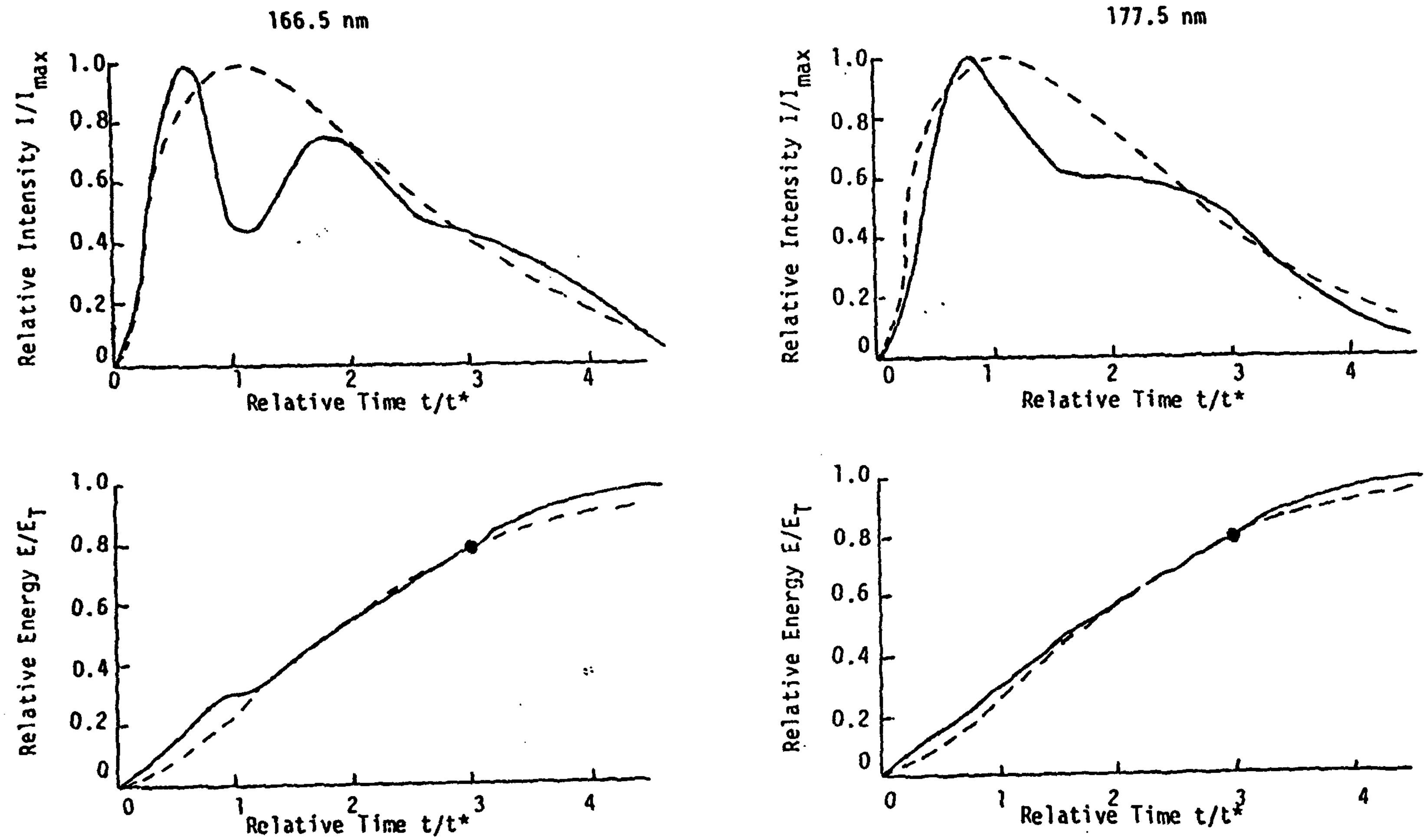
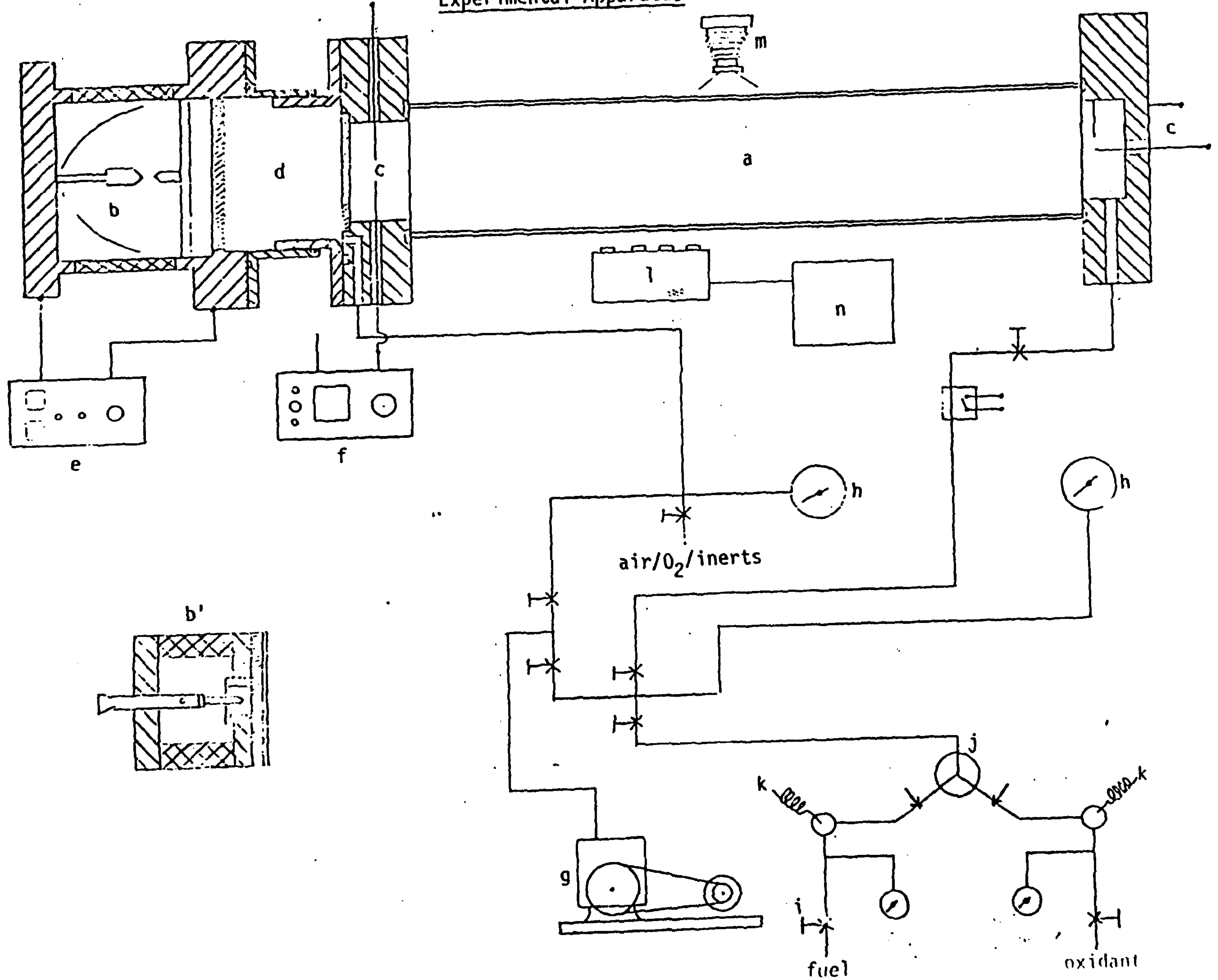


Figure 2 - (Continued) - *Relative Values of Intensity and Energy vs Time for Pulsed VUV Light Source: Experimental (Solid Curve), Critically Damped Representation (Dashed Curve)*

Figure 3

Experimental Apparatus



Legend for Figure 3

Experimental Apparatus

a - combustion chamber

b - EIMAC light source (b' - ILC)

c - spark igniters

d - intervening cell

e - power supply for light ignition

f - power supply for spark ignition

g - vacuum pump

h - pressure gauge

i - needle valve

j - mixing chamber

k - solenoid valve

l - photodetector subsystem

m - movie camera

n - oscilloscope

(1) *ILC - A pulsed xenon point source with a 0.6 cm diameter* flat, sapphire window is used to provide radiation in the 140-200 nm spectral region. Energy input in the 0.5 to 50J range is provided by controlled capacitor discharge with pulse periods ranging from 100 to 200 μs.

(2) ORC - A continuous mercury-xenon source with quartz optics provides up to 7 kW of energy and operates in the 200-400 nm spectral region. Optics provides for either a parallel (8 cm diameter) or focused beam of light.

(3) EIMAC - A continuous xenon point source is used in combination with a lower grade sapphire window and an elliptical reflector (sealed in the arc chamber) to provide a focused source of radiation in the 150-400 nm spectral region. This source can be operated in the continuous mode at a power level up to 500 W, and has also been used in the pulsed mode at energy levels of up to 50J.

The capabilities and specification of the current light source used in this experimental work were summarized in Table 1.

A mixing chamber equipped with needle valves and pressure gauges ensures accurate and reproducible equivalence ratios of the various gaseous combustible mixtures. A photodetector array and a motion movie camera are used to record flame propagation speeds following the ignition process.

The static experiments have been divided into two subjects: ignition and enhancement. Combustion ignition is achieved by using either a light source or in-situ spark discharges, or a combination of both. The light source is fixed on the left-hand side of the combustion tube while the spark electrodes can be discharged on either side of the tube resulting in a flame propagating into or away from the light source. Ignition has been attempted by using a pulsed light source (ILC) and a continuous light source (EIMAC). Combustion enhancement has been investigated using both continuous light sources (ORC and EIMAC).

Ignition: Various gaseous fuel/air and fuel/oxygen mixtures have been successfully ignited by using only a light source (no thermal effects). A few of the reactive mixtures ignited by the pulsed ILC light source are hydrogen/oxygen, methane/air and propane/air. The experimental variables besides the reacting mixtures were equivalence ratio, combustion chamber pressure and power of the light. The gases were admitted to the combustion chamber at predetermined equivalence ratios and pressures and then the light source was turned on. If the mixture did not ignite the power supplied to the light was increased until by trial and error the critical power for ignition was found.

Following this procedure a series of radiative ignition tests were performed with stoichiometric hydrogen-oxygen mixtures using ILC VUV pulsed lamps. Employing a reference condition of 40 kPa (300 torr) pressure, a *minimum* stored energy requirement for ignition using the ILC pulsed VUV sources was determined to be about 500mJ. This is in agreement with previous results for sources of the same generic design which indicated minimum ignition energies on the order of 250mJ.

By using a combination of multiple sapphire windows (up to three), various air gaps between two windows, and various window opening diameters, a measure of the degree of VUV beam spreading was obtained. Although it has been conducted on a preliminary basis, it indicates that the pulsed VUV source can be considered as a point source located between the central electrode and rear window surface. As a result, extensive beam spreading occurs and penetration of fuel-free boundary layers (even if oxygen free) will require a substantial energy increase. Based on these preliminary results, the estimated energy increase required to achieve radiative ignition with the present point light sources after penetration of various fuel-free air layers is shown in Figure 4. For comparison, the corresponding requirements for parallel and focused beams are also illustrated. The curve for the point source represents the effect of energy loss due to beam spreading and oxygen absorption while the curves for parallel and focused beams represent oxygen absorption only. A concentrating factor of 10 was assumed for the focused beam. Allowing an energy increase by a factor of 10 (hydrogen-oxygen ignition would now require 5J of input energy) would permit air layers of about 0.15 cm (0.060 in) to be penetrated. This distance can be extended to about 0.40 cm (0.157 in) by using a parallel beam and about 2.1 cm (0.83 in) by using a focused beam. Application of the radiative ignition technique where fuel-free air boundary layers are present would benefit substantially by the development of parallel beam and particularly focused beam VUV sources.

Extensive propane-air radiative ignition tests, using ILC pulsed light sources, were also conducted under static conditions [3]. Successful ignitions were obtained and minimum ignition energies were determined for various equivalence ratios at atmospheric and subatmospheric pressures. Figure 5 depicts typical results of minimum ignition energy versus equivalence ratio for a propane-air mixture.

All measurements were made at room temperature (about 20°C), under two chamber pressures: 1 atmosphere and 500 torr and with two ILC light sources designated as #3 and #9. A minimum spark ignition energy reproduced from Reference 4 was drawn on the figure for comparison. It is noted that the minimum radiative ignition energy curves are similar in shape to the spark ignition curve, namely, a minima of the ignition energy occurs at some equivalence ratio. Increasing or decreasing the equivalence ratio from the value corresponding to the minima results in an increase in light as well as spark ignition energies until the equivalence ratios are outside the flammability limits and all attempts to ignite fail. It is important to note that light minimum ignition energy occurs at a leaner equivalence ratio than that of spark ignition, and that light minimum ignition energies are less sensitive to pressure variations than spark ignition.

The significance of the successful pulsed light source ignition experiments is two-fold: it reconfirms the concept of radiative ignition, and it demonstrates technical achievement in the design of an advanced optical radiative igniter, which was the result of a collaboration with ILC.

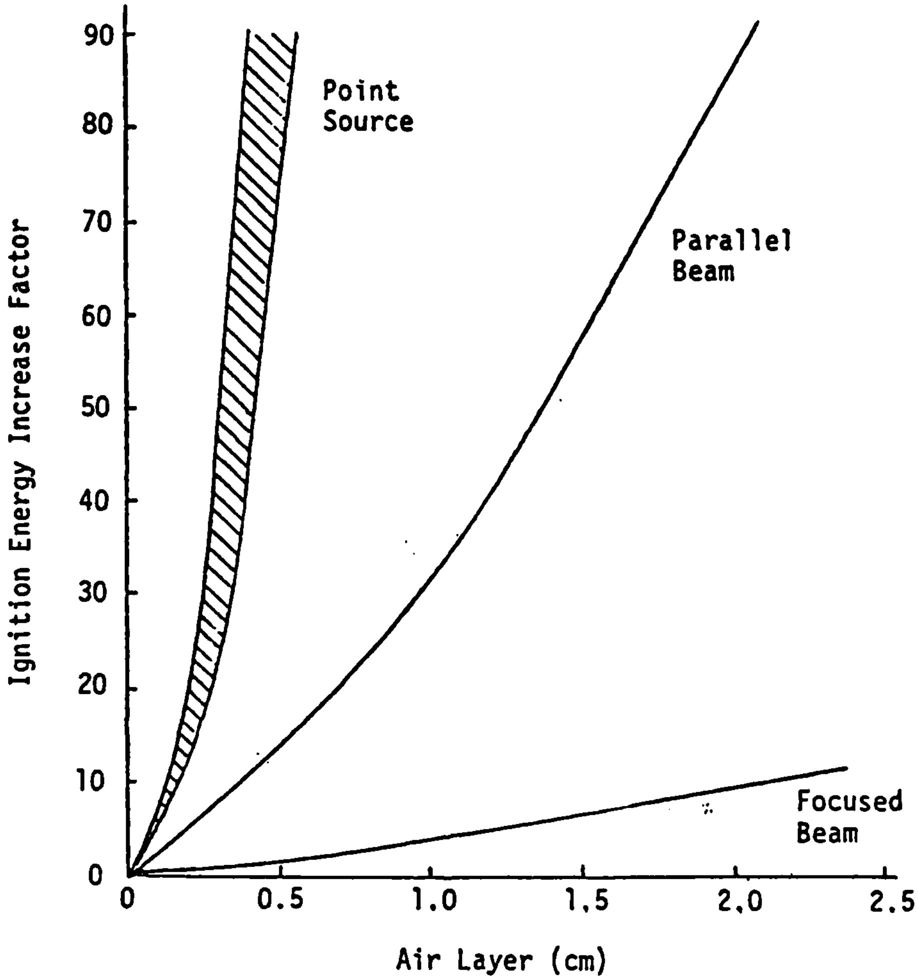
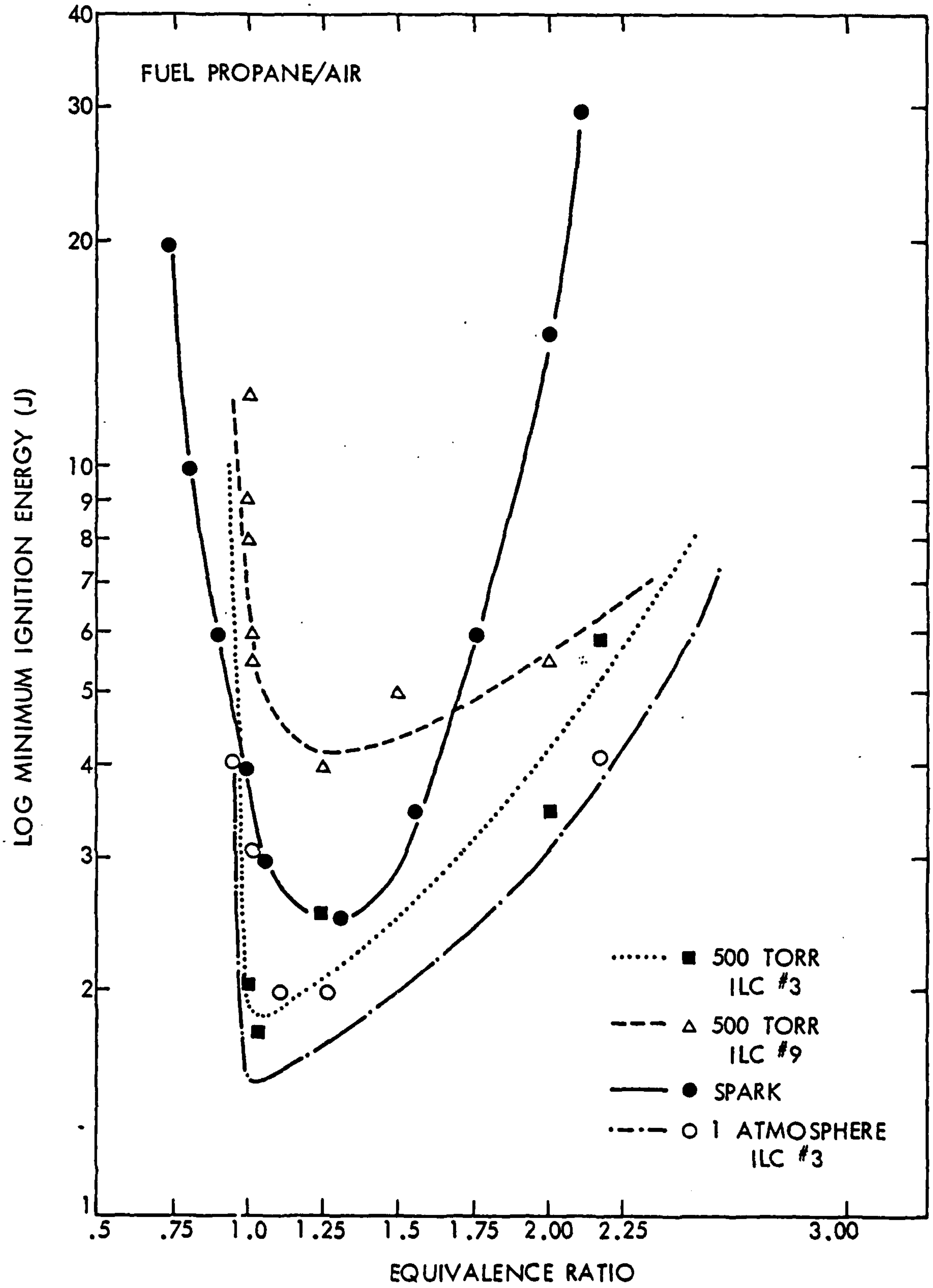


Figure 4 - Estimated Energy Increase Required to Achieve Radiative Ignition After Penetration of an Air Layer at 800 K and 101.3 kPa

FIGURE 5

MINIMUM SPARK AND RADIATIVE IGNITION ENERGIES VS. EQUIVALENCE RATIO AT (SUB)ATMOSPHERIC PRESSURE



For the first time, radiative ignition was demonstrated with a continuous light source (EIMAC). The premixed gases were propane-oxygen at stoichiometric ratio and at atmospheric pressure. The lamp cracked during the experiment and a new one was ordered. The first reported successful ignition with a continuous light source implies the potential possibility of using the light as an optical-radiative flame stabilizer with zero pressure drop instead of the conventional flameholders.

Combustion enhancement: Combustion enhancement experiments were conducted with propane/air mixtures at various equivalence ratios and pressures. The average flame propagation velocity is used to evaluate combustion enhancement. It is defined as the average velocity at which the luminous flame front travels throughout the combustion tube (it is not the burning velocity). The calculated flame propagation velocities were compared under light and no light conditions for otherwise identical conditions. Figure 6 depicts such one comparison. The light source is EIMAC irradiating from the left-hand side of the combustion chamber while the spark igniter is discharged from the right-hand side causing the flame to propagate from right to left, into the light source.

The enhancement in terms of average flame propagation velocity is very small at lean mixtures and becomes more substantial at stoichiometric and rich mixtures (up to 15-20%) at atmospheric pressure. At subatmospheric pressure significant enhancement of 10% was obtained at an equivalence ratio of unity and it decreased at lean and rich mixtures to only 2-3%.

Other measurements used to evaluate combustion enhancement for marginal flames were extinction distance and extinction time. The former is the propagation distance of the flame along the tube until extinction, and the latter is the time recorded from ignition until extinction. The experiments were conducted with the light source and the spark electrodes both on the left-hand side of the combustion chamber. Table II summarizes the results. It is shown that for marginal flames (near the lean flammability limit) the extinction time and extinction distance are increased under continuous irradiation of the EIMAC light source. The former is increased by up to 80% and the latter is increased by 15-25%. No enhancement has been detected when the ORC continuous light source has been used.

These very encouraging experimental results of combustion enhancement in terms of higher flame propagation velocities and larger extinction times and extinction distances can be construed as an extension of the general flammability limits by the use of a VUV continuous light source.

- Radiative Analytical Model

The modeling effort on radiative initiation and enhancement of hydrogen-oxygen-nitrogen mixtures has progressed. The model includes the effect of light source characteristics; photodissociation of light absorbing species; reactant mixture kinetics, including electronically excited state species; and adiabatic temperature rise due to reaction heat release. The species considered in the radiative initiation and enhancement model for the H_2-O_2-N_2 system are listed in Table III. A literature review was

FIGURE 6

FLAME PROPAGATION VELOCITY VS. EQUIVALENCE RATIO
AT (SUB)ATMOSPHERIC PRESSURE AND
UNDER VUV LIGHT/DARK CONDITIONS

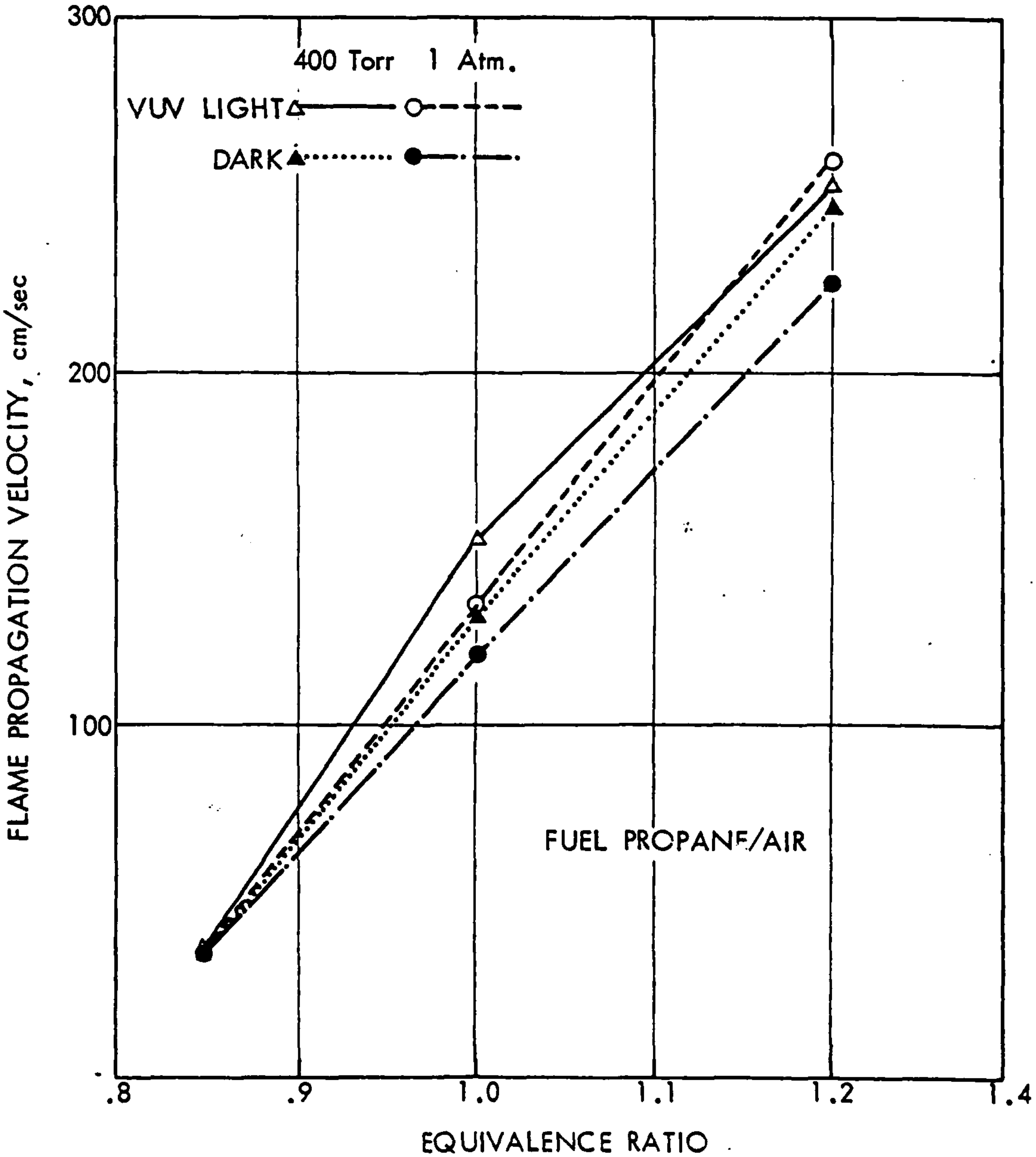


TABLE II

EXTINCTION TIMES AND DISTANCES
FOR MARGINAL PROPANE-AIR FLAMES

Equivalence Ratio	Pressure	Dark/Light	Extinction Time (frames)*	Change %	Extinction Distance (cm)	Change %
.82	1 atm	Dark	20.0		13.9	
		Light	36.3	+81	17.4	+25
.82	400 torr	Dark	18.0		17.3	
		Light	30.0	+67	21.0	+21
.78	607 torr	Dark	41.5		24.2	
		Light	50.0	+20	28.0	+15

* 64 frames = 1 sec

TABLE III

HYDROGEN-OXYGEN PHOTOCHEMICAL SYSTEM

REACTANT SPECIES

$O(^1D)$	O_2	OH
O	O_3	H_2O
$O_2(^1\Sigma_g^+)$	H	HO_2
$O_2(^1\Delta_g)$	H_2	H_2O_2

PHOTODISSOCIATION REACTIONS

O_2	$+ h\nu\ (\lambda < 245)$	$\rightarrow O$	$+ O$
O_2	$+ h\nu\ (\lambda < 175)$	$\rightarrow O$	$+ O(^1D)$
O_3	$+ h\nu\ (\lambda < 1140)$	$\rightarrow O_2$	$+ O$
O_3	$+ h\nu\ (\lambda < 310)$	$\rightarrow O_2(^1\Delta_g)$	$+ O(^1D)$
O_3	$+ h\nu\ (\lambda < 260)$	$\rightarrow O_2(^1\Sigma_g^+)$	$+ O(^1D)$
H_2O	$+ h\nu\ (\lambda < 242)$	$\rightarrow OH$	$+ H$
HO_2	$+ h\nu\ (\lambda < 456)$	$\rightarrow OH$	$+ O$
H_2O_2	$+ h\nu\ (\lambda < 365)$	$\rightarrow OH$	$+ OH$

undertaken and best values for the rate constants in the form AT^{-B} exp (-CT) for reactions involving these species were obtained. The current version of the model considers approximately ninety such reactions. The minimal set required and a sensitivity analysis of the rate data for those dominant reactions is under investigation as part of the new contract.

Based on the model results, a new mechanism for radiative enhancement of combustion has been formulated. The mechanism involves the influence of photon generated oxygen atoms on combustion reaction kinetics wherein the realization of reduced reaction time results in enhanced flame propagation. Further details on the modified enhancement mechanism, the modeling approach taken, and some initial modeling results, were reported in the first and second contract reports.

Other model results indicate a beneficial effect of moisture on the ignition process and the existence of an optimum pulse period for ignition. The improvement in ignitability by the addition of moisture to the reactant mixture has been verified experimentally as indicated by results described in the following section. It appears that water vapor acts as a sensitizer by participating in photon absorption and then dissociating into hydroxyl and hydrogen radicals. Optimum pulse periods were calculated to be on the order of 10 to 20 μs for radiative ignition. Although experimental pulse periods this short have not been used, a trend of decreased ignition energy with decreasing pulse duration in the range 320 to 60 μs agrees with this result. A long radiant pulse is undesirable since a buildup of high oxygen atom concentrations is prevented by loss mechanisms such as atom recombination or ozone formation. However, it appears desirable to save some of the photon energy which results in dissociation until the reactant mixture temperature increases to the point where more rapid use of constructive oxygen atom reactions result. Consequently, very short pulses should also be avoided.

The initiation model, as indicated above, has shown good phenomenological agreement with experimental results.

The analytical results have been used to investigate the phase plane diagram for given hydrogen-oxygen mixtures. The reaction paths for various pulse intensities have indicated combustion initiation by the attainment of critical temperature and oxygen-atom concentration in a time less than an assumed characteristic heat loss time. An explicit heat loss mechanism was added to the model to allow further study of the phase plane and the dependence of the separatrix (between stable and combustion regions) upon the assumed heat loss mechanism and associated parameters. Preliminary results suggest that the phase plane configuration depends more strongly on the underlying kinetics than on the precise form assumed for the heat loss. Initially, a simple linear heat loss term was used.

Work has already begun on expanding the initiation model to include species diffusion and associated boundary conditions. The function and Jacobian subroutines have been modified to include the appropriate terms. In the new contract period we shall integrate the resulting equations and compare the results to those of the simpler model to examine the effect of diffusion and wall recombination upon combustion initiation. The first integration approach to be used will be the numerical method of lines with the spatial variable discretized either by finite difference or collocation with splines techniques. This work can then provide the basis for the possible subsequent inclusion of the more detailed hydrodynamics required to investigate combustion enhancement.

- Catalytic Analytical Model

A model of new catalytic flameholding devices has been developed, in part under the National Science Foundation Industrial Research Participation Program. This model is based on the usual wake recirculation formulation, as influenced by the work of Zukoski and Marble [5,6] on critical ignition times. The split of flow through and around the catalytic monolith is determined by pressure drop considerations. The flow into the recirculation zone is thus the sum of the flow through the monolith and that resulting from turbulent inclusion. The distance needed for a flame to develop is predicted as a product of mean convective velocity and reaction time obtained from the analysis of Kunder et al [7] and compared to a recirculation zone length calculated on the basis of flow parameters. The comparison of these lengths allows the determination of blow-out or flameholding.

In this way, the existing model allows:

(1) Description of the influence of overall geometry, blockage ratio, and substrate configuration on aerodynamic and thermodynamic variables, especially pressure drop.

(2) Determination of the degree of approach flow penetration through the catalytic section, recirculation zone size and shape, and shear layer characteristics.

(3) Description of the concept's ability to widen stability and ignition limits and to widen the cross-sectional area occupied by the stabilization devices.

During the contract period, we carefully reviewed this model, especially focusing on the assumptions in the following areas:

1. Flow split

2. Characterization of catalytic flameholder effluent

3. Wake recirculation formulation

4. Flameholding/blow-off determination

After the review has been completed, it has been proposed in the new contract that any of these areas which we believe were not adequately treated in the current model will be revised to produce a sufficiently detailed, realistic, and balanced model. Modifications required to bring the existing computer program into conformity with the revised model will be made. Model predictions will then be compared to experimental data as they become available. Where lack of agreement is noted, we shall endeavor to identify its causes and revise the model until good agreement is obtained in the regimes of interest. The resulting analytical tool will be used as an adjunct to the experimental effort to broaden our understanding of the underlying aerothermochemical interactions and as an aid in performance optimization.

- Initial Catalytic Testing

The selection and design of experimental phototype flameholders for concept confirmation have been completed. Four configurations were proposed as shown in Figure 7. The first configuration is a disk, 50 mn in diameter and 6 mn in thickness. This disk is used to determine the cold flowfield behind a bluff body. The second configuration is a cylinder with the same diameter as the disk and a length of 38 mn. The flowfield behind it is compared with the flowfield of the disk to study the effect of the length, needed for adequate catalytic surface, on wake recirculation. The third configuration is a monolith having the same dimensions as the cylinder. The monolith is used to study the effect of the open channels on the non-reacting flow conditions. The last configuration is a monolith, as the third configuration, but coated with a catalyst. The catalytic prototype is the most important configuration. It is primarily designed to prove the concept of catalytic flameholder. Subsequently, it will be used for screening chemical and physical characteristics to determine the best candidates for flame stabilization tests.

The conceptual design of this catalytic prototype has further evolved from its initial configuration of straight uniform cells to graded cells and finally to converging cells. This concept evolution is depicted in Figure 8. The idea of graded cells was promoted during the Third Workshop on Catalytic Combustion, and it offers an increase in resistance to blow-out and an increase in throughput. The converging cells (slots) design was suggested to us by W. B. Retallick at the Fourth Workshop on Catalytic Combustion. This design, in addition to offering the same advantages as the graded cells, exhibits also smooth convergence (no stepping down) and upstream heat radiation. The smooth convergence ascertains better flow characteristics and suggests easier fabrication. The upstream radiation enhances initial surface reaction close to the inlet where ignition occurs, and where combustion is most unstable. Other features for consideration include the material of the substrate (metal vs. ceramic), and the ease in cost of fabrication.

All the configurations will be assessed and the most promising ones will be experimentally evaluated and compared to the baseline performance obtained by the conventional V-gutter flameholder.

- Test Facility

A Plug Flow Combustor (PFC) has been designed and fabricated to study both catalytic and radiative augmented combustion tests under flow conditions. The PFC depicted in Figure 9 is a highly flexible device which can be used to study combustion under plug flow conditions up to fairly high gas velocity (200 m/s). The test section consists of a 4-inch internal diameter and 48 inch long combustor fabricated from 0.474 inch wall Inconel 600 pipe. It has 10 optical ports spaced on 8-inch centers to allow the use of advanced laser diagnostics, and the use of VUV light

Figure 7

Catalytic Flameholder

New Design for Concept Confirmation

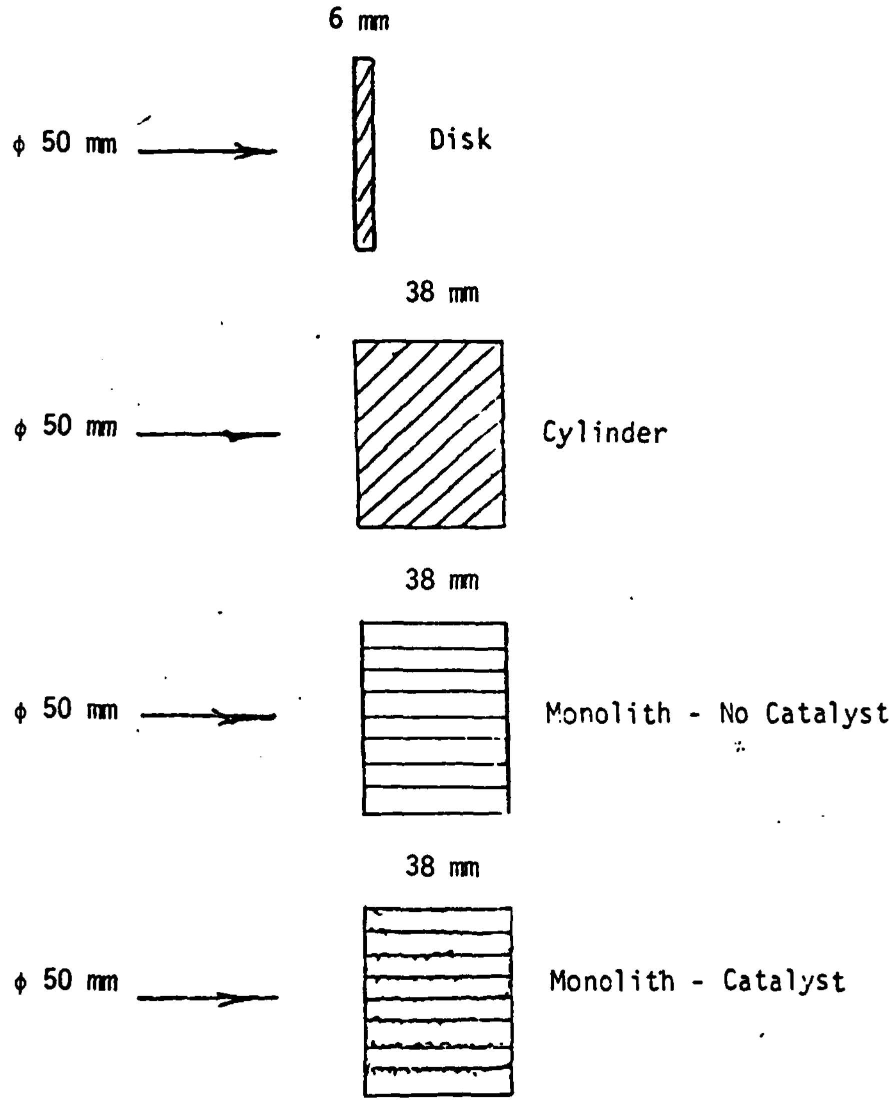
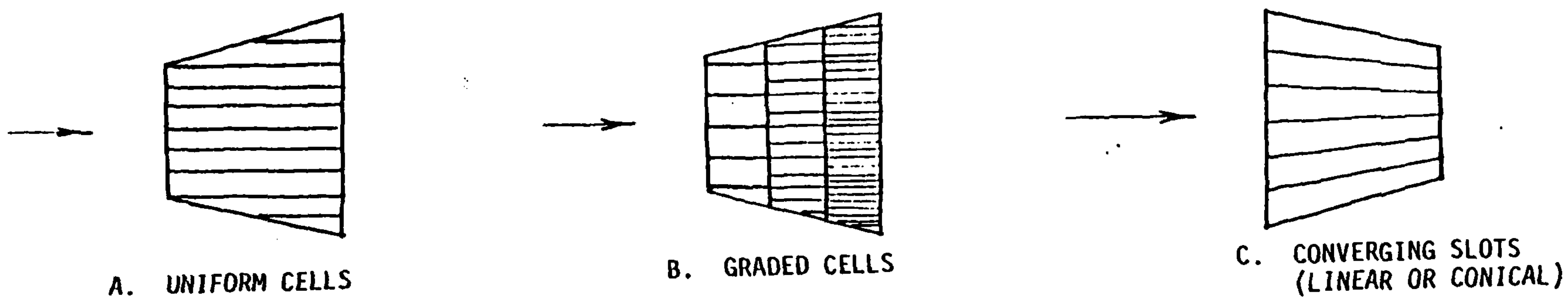


FIGURE 8

CATALYTIC FLAMEHOLDER

CONCEPTUAL DESIGN



FEATURES FOR CONSIDERATION:

MATERIAL: CERAMIC VS. METAL

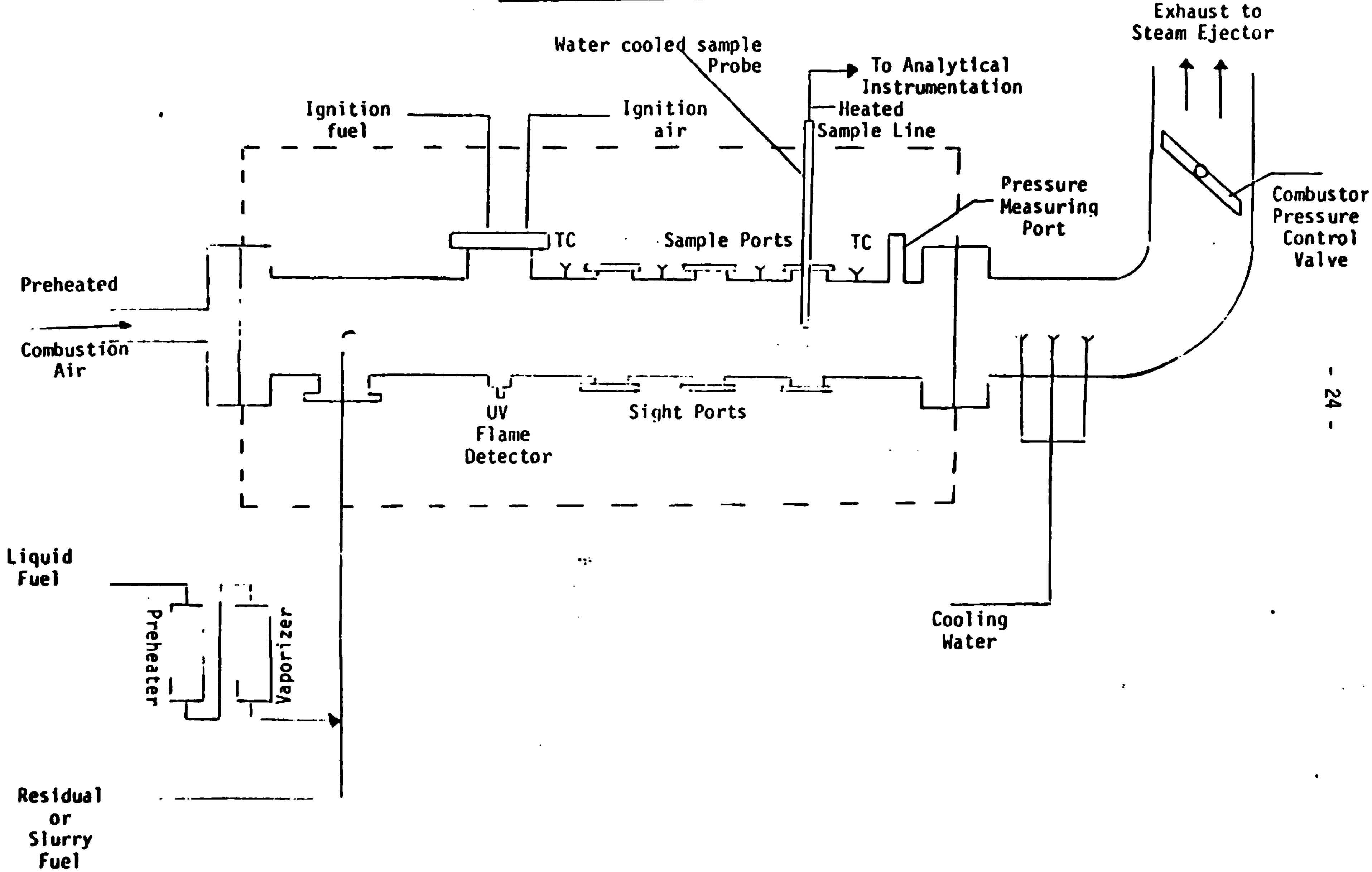
FLOW: GRADED VS. STRAIGHT FLOW PATH

COMBUSTION: COMPLETE VS. PARTIAL

CONSTRUCTION: COMPLEX VS. SIMPLE

FIGURE 9

PLUG FLOW COMBUSTOR SCHEMATIC



sources. The PFC is a modular unit which was designed to be accommodated and readily interchanged on the Combustion Science Research Facility. Therefore, its capability and limitations are determined by the support systems of the general Combustor Facility. The main capabilities of the test apparatus are:

Equivalence Ratio:	0.2-1.0
Pressure:	1 atm
Air Velocity:	up to 200 m/s
Air Temperature:	up to 1000°K

The combustion facility is equipped for accurate determination of combustion product gas composition, combustion efficiency, combustor temperature, pressure, fuel flow, and air flow. The gas analysis train includes instrumentation for determination of CO, CO_2, NO, NO_x, O_2, and total hydrocarbon. Additional instrumentation, wet chemical analysis, or gas chromatographic capability can be provided to determine SO_2, HCN, NH_3, H_2, or hydrocarbon identification. Recently, the facility has been also equipped with three advanced optical systems for better diagnostics of the flowfield, species concentration and droplet size distribution. The systems are: (1) Schlieren by Space Optics Research, (2) Laser Doppler Velocimetry by TSI and (3) Malvern. Outputs from all existing instrumentation is logged into the site's pilot plant computer system and on-line analysis is performed to report (via teletype) to the operator the status of the experimental information being acquired.

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PROFESSIONAL PERSONNEL
ASSOCIATED WITH RESEARCH EFFORT

Dr. Moshe Lavid - Principal Investigator - PhD Mechanical Engineering, State University of New York at Stony Brook, 1974.

Dr. L. A. Ruth - Group Head - PhD Chemical Engineering, City University of New York, 1973.

Dr. A. E. Cerkanowicz - Previous Principal Investigator, Combustion Consultant - PhD Mechanical Engineering, Stevens Institute of Technology, 1971.

Dr. W. Bartok - Previous Group Head - PhD Physical Chemistry, McGill University, 1957

Dr. W. S. Blazowski - Combustion Consultant - PhD Mechanical Engineering, Stevens Institute of Technology, 1970.

Dr. J. G. Stevens - Analytical Consultant - PhD Courant Institute of Mathematic Sciences, New York University, 1972.

INTERACTIONS/OUTSIDE INTEREST

A. Talks and Papers

Two internal (Exxon) presentations on the program were made to management and professionals on September 26, 1977 and May 12, 1978. Presentations were also given at the following AFOSR Contractor's Meetings: Air-Breathing Combustion Dynamics, West Lafayette, Indiana (Purdue University), September 12, 1977; Unconfined Fuel-Air Explosions and Other Combustion/ Explosion Related Research, Champaign, Illinois, November 21, 1977.

A paper entitled "Radiative Augmentation of Combustion: Modeling" was presented at the Eastern States Section Combustion Institute meeting on Chemical and Physical Processes in Combustion on November 28-29 and December 1, 1978.

Presentations were given at the following AFOSR Contractor's Meetings: "Mechanisms of Radiation Augmented Ignition and Combustion," Air-Breathing Combustion Dynamics and Kinetics, Dayton, Ohio, October 1978; "Radiative Augmentation of Combustion," Meeting and Workshop on Unconfined Detonations and Other Explosion Related Research, Fort Walton Beach (Eglin AFB), Florida, January 1979.

A paper entitled "Case Studies in the Simulation of Novel Combustion Techniques" was presented at the 1979 Summer Computer Simulation Conference, July 16-18, 1979, Toronto, Canada.

Two additional internal (Exxon) presentations on the program were made to management and professionals on March 5, 1980 and April 16, 1980. Two presentations were also made at the last AFOSR Contractor's Meeting on "Air Breathing Combustion Dynamics and Kinetics," Alexandria, Virginia, January 1980. The first presentation was entitled "Catalytic Flame Stabilization," and the second one was entitled "Radiation Augmented Combustion."

Two more presentations were given at Sandia Laboratories, Albuquerque, New Mexico, February 8, 1980, and at the 4th Workshop on Catalytic Combustion, Cincinnati, Ohio, May 14-15, 1980. The former presentation was on "Photochemical Ignition and Combustion Enhancement," and the latter one was on "Catalytic Flame Stabilization."

One presentation entitled "Photochemical Initiation of Combustion" was made at Imperial College, London, April 21, 1980.

B. Interest Expressed by Other Scientists

Although a strong interest is expressed in our combustion augmented program, as can be seen by the many requests for additional technical information listed below, it seems that the only ongoing active work that is directly related to our radiative approach is the plasma jet work of Professor Felix Weinberg at Imperial College, London. Prof. Weinberg has carried out experiments and has reported encouraging combustion augmentation results by using chemical and fluid mechanical effects via his novel design of a plasma jet. The kinetics is modified by a supply of radicals from the plasma (especially H atoms) while the fluid mechanics is modified by the high velocity jet. The plasma jet demonstrated ignition of sub-lean mixtures, increased flame speeds and conversion rates. The current design is using a pulsed plasma jet, ... there may be a need for developing a continuous plasma jet plug. Open communication has been established with Prof. Weinberg and he has been retained as a consultant to Exxon Research and Engineering and this program.

The work by R. Knystautas and J. H. Lee at McGill University on Photochemical Initiation of Detonation in Gaseous Explosive Media makes specific use of the photochemical ignition concepts being explored by the Exxon work. The McGill work is funded in part by AFOSR (Grant 72-2387E) and by the National Research Council of Canada (Grants A-6891, A-3347 and A-118). Contact and information exchange with this group has been maintained.

Contact has been made with Mr. Raymond DeMaris of RIGS Corp. (Reactant Intermediary Generations Systems). This group is working in the area of photochemical combustion enhancement of sensitized reactant systems. A meeting was arranged in August, 1979 to explore mutual interest and exchange information in this technical area.

John Manheim of Wright-Patterson Air Force Base has expressed interest in our computer model of photochemical combustion effects. Their studies of laser ignition of aircraft fires could benefit substantially by the model we have developed under AFOSR contract. We indicated that our immediate effort does not provide the necessary documentation of the program to allow for its use by others. Documentation is part of our program effort that would be undertaken during the final reporting procedure.

Contact has been made with Don Brunda and Bill Wagner of the Naval Aeropropulsion Center, Trenton, New Jersey. They have been following our work in the radiative ignition area and have been approached by ILC to fund a small program involving photochemical ignition of jet fuel.

In the catalytic work, contact has been made with Dr. W. B. Retallick who has recently become a consulting engineer after being for several years a Vice President for R&D at Oxy Catalyst. Dr. Retallick has a strong interest in the development of the catalytic flameholder and believes that it can be utilized as a partial combustor, resulting in lower catalyst temperatures. Dr. Retallick has been retained as a consultant and he will provide the catalyst for the prototype flameholder.

During the entire research period, additional requests for technical information were received from the following professionals:

Prof. M. J. Antal, Jr., Princeton University, Princeton, N.J.

Prof. J. M. Calo, Princeton University, Princeton, N.J.

Dr. F. E. Fendell, TRW, Redondo Beach, California

Dr. M. Gusinow, Sandia Laboratories, Livermore, California

Dr. Robert Hicklin, GM Corporation Research Laboratories, Warren, Michigan

Prof. A. K. Oppenheim, University of California, Berkeley, California

Dr. W. B. Retallick, Consultant, West Chester, Pennsylvania

Mr. Marvin Smith, Independent Consultant, Munice, Indiana

Prof. M. Summerfield, Princeton Combustion Laboratories, Princeton, N.J.

SUMMARY: POTENTIAL APPLICATION OF RESEARCH RESULTS

Both the radiative and catalytic techniques have demonstrated the capability to enhance combustion processes and to broaden normally encountered stability limits.

The work on radiative ignition and combustion enhancement is providing fundamental information on a unique combustion process. Concepts which represent a new departure and extension of conventional combustion practice can evolve from the experimental data being obtained. Aspects of the radiative ignition and enhancement concept have been demonstrated in our laboratory under static (no flow) conditions. Successful pulsed light source ignition experiments reconfirm the radiative augmented concept and demonstrate the technical feasibility of designing an advanced optical-radiative igniter. Successful ignition with a continuous light source implies the possibility of using the light as an optical radiative flame stabilizer with zero pressure drop instead of the conventional flameholders. Preliminary encouraging results of combustion enhancement in terms of higher flame propagation velocities and larger extinction times and distances demonstrate a potential opportunity to extend the combustor operating limits utilizing the radiative technique. It is construed that the enhanced flame propagation can be translated into higher combustion rate and extended flammability limits.

From the experimental results reported here we gain confidence that radiative augmented combustion is a potentially viable technique to extend current aircraft operating limits. Eventual application to gas turbine engine systems is envisioned both for improved combustor operation and flameholding. Some future areas of potential application are: High altitude combustor reignition following flame-out, drag-free flame stabilization in supersonic combustors, and added flexibility for conventional combustors to use future alternate fuels. To this end, radiative ignition and combustion enhancement experiments under flow conditions are required as well as continued VUV light source development in the direction of improved beam optics.

The catalytic flame stabilization concept is particularly important to aeropropulsion combustion: turbo propulsion mainburners, afterburners, duct burners and ramjet dump combustors. Potential benefits include improved ignitability, stability as well as efficiency, and combustion design flexibility for alternate fuel usage. In the afterburner application, the conventional bluff-body flameholder can be replaced by a porous catalytic device resulting in less pressure drop than a solid flameholder of equal cross-sectional area. It can broaden its stability range by allowing for operation at inlet velocities, temperatures and fuel mixtures where conventional flameholders begin to fail. In addition, it may have the advantage of being a passive autoignition device.

Finally, a potential opportunity exists for the development of an advanced combustor featuring the combined performance of catalytic stabilization and radiative enhanced combustion.

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Unsensitized Ignition	Oxygen Photodissociation	Flameholder
Vacuum Ultraviolet Radiation	Flame Propagation	Stability Limits

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This final report summarizes research in Radiation/Catalytic Augmented Combustion. This research encompasses two promising techniques for extending aircraft operational range. They are radiative and catalytic augmentation techniques to enhance combustion initiation, and reaction kinetics which restrict combustor operation via limits on flammability, flame propagation, ignition and stability. Both techniques have demonstrated the capability to enhance combustion processes and to broaden normally encountered stability

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ABSTRACT (Contd.)

limits. The radiative technique under laboratory static conditions has successfully ignited fuel-air mixtures, and has enhanced combustion processes, utilizing pulsed and continuous VUV light sources. Similarly, the catalytic technique has provided efficient combustion under normally difficult fuel lean, low temperature conditions. A complementary effort involves the development of analytical capability required for modeling the radiative and catalytic techniques.